Thermal Fatigue in Copper Wire Bonds under Power Cycling: Acceleration Model and Influence of Different Wire Types

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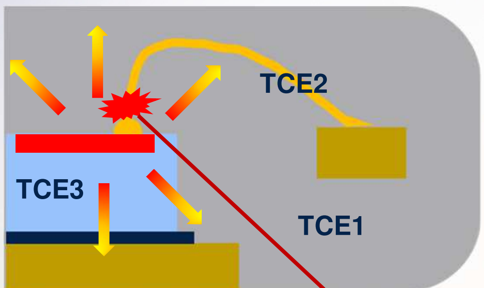
Thermal Fatigue in Cu Wire Bonds under Power Cycling

Copper wire thermal fatigue caused by the active cycling of power stages is gaining an increasing relevance for smart power products



THERMO-MECHANICAL MISMATCH

WHY

Growing power density and sharper temperature gradients to be managed without compromises on lifetime

DETECTION

First impact on HTOL high accelerated test due to high junction temperature

Tj_avg=150 ÷175°C and high temperature swing ΔTj = 50÷120°C

Wire crack found in range of tens of thousands of cycle

Thermal Fatigue in Cu Wire Bonds under Power Cycling

Reliability characterization is becoming necessary

PILOT EXPERIMENT

Characterization done on 1.2mil Cu wire
- 4N copper wires tested in three different stress conditions.
- 4N, 2N, and PCC wire types compared

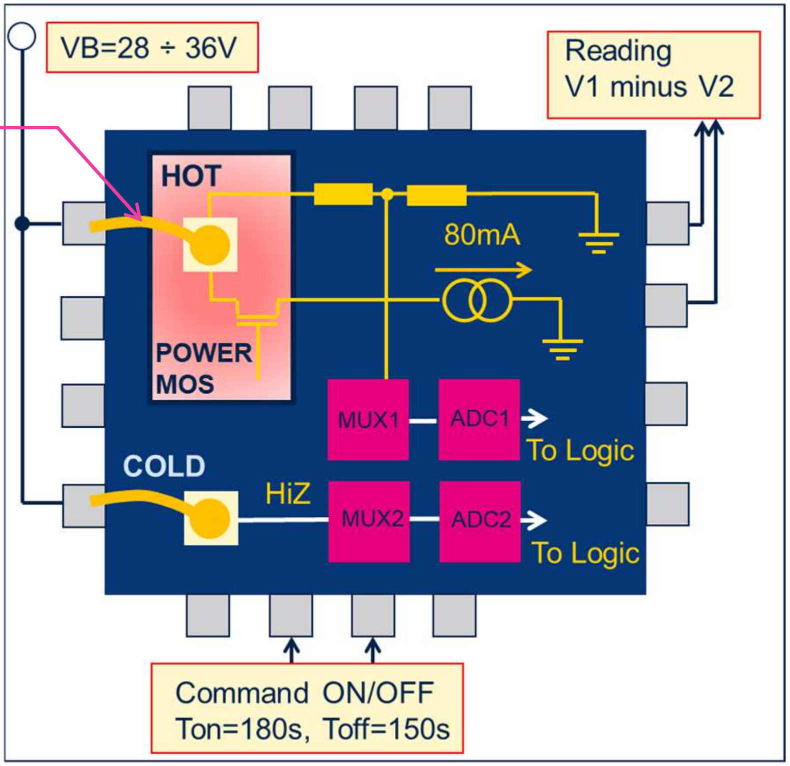
EXPERIMENT DESCRIPTION AND RESULTS

- EXPERIMENTAL SET-UP
- TRIAL
- OUTCOME
  - Wire performance comparison results
  - Acceleration Model Proposal
  - HTOL prediction example
  - Failure Mechanism
- CONCLUSION and NEXT STEPS

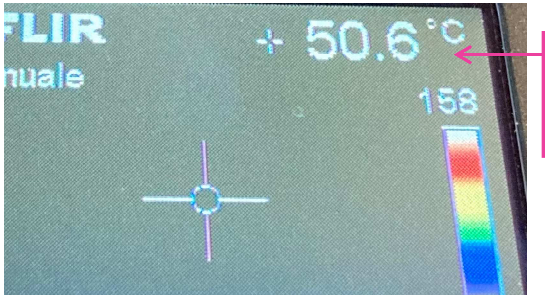
Test Vehicle and Experimental Set-Up

TEST VEHICLE : BCD (RDL option) Product / Package TQFP / Copper Wire 1.2mils
EQUIPMENT : HTOL board
STRESS RECIPE : Customize to apply power cycle and to monitor the resistance of the worst-case wire bond

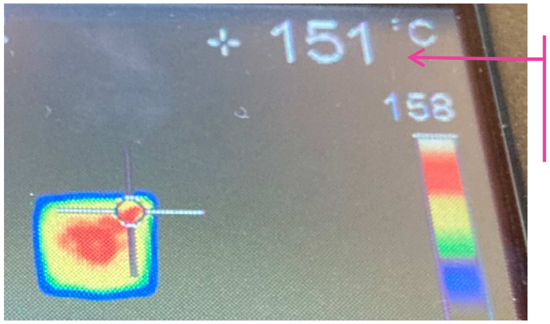
Monitored wire
Worst-case ON/OFF thermal swing



Wire bonding temperature (Twire) = Tcase top



Twire OFF (Toven)



Twire ON

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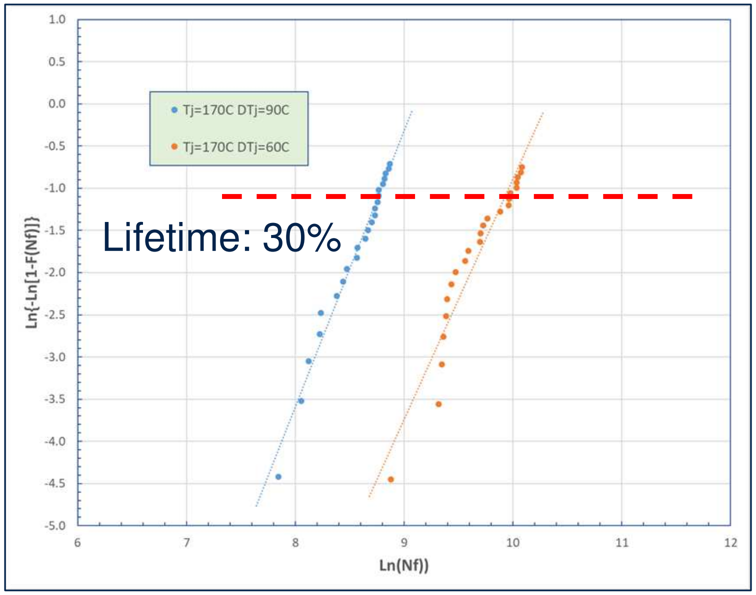
Wire bonding crack is detected as a sudden voltage drop increase

The number of cycles to failure of each DUT is recorded, CDF is plotted on Weibull Chart



TRIALS and PHYSICAL ANALYSIS TECHNIQUES

Cu pure 4N wire is Tested Under Different Stress Conditions and Compared with Cu-alloy and PCC Wires

WIRE Type	Twire ON	Twire OFF	ΔTwire
Cu pure 4N (soft)	170°C	110°C	60
Cu pure 4N (soft)	140°C	50°C	90
Cu pure 4N (soft)	170°C	80°C	90
Cu pure 4N (hard)	170°C	80°C	90
Cu-ally 2N	170°C	80°C	90
Pd-coated Cu 4N	170°C	80°C	90

Trails allow both failure mechanism and acceleration model investigation

Extensive physical analysis for failure mechanism investigation

- **Curve Tracer Pin to Pin** to check wire bonding failure
- **SAM analysis** to exclude major delamination
- **Wire inspection after de-cap**
  - Optical Microscope and SEM
- **Wire Cross section SEM analysis**
  - SE (Secondary Electron)
  - BSE (Back Scattered Electron)
  - EDX (Energy Dispersion Xray)
  - BSED (Back Scattered Electron Diffraction)

Both virgin parts and failed parts after test were inspected for all trials

WIRE PERFORMANCE COMPARISON

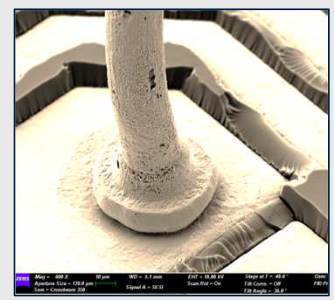
- **Cu pure 4N wire soft /hard same behavior**
- **Cu-ally wire 2N improves robustness**
- **Pd-coated Cu wire best performance**

WIRE Type	Twire ON	Twire OFF	∆Twire	Ncy to 30% failure
Cu pure 4N (soft)	170°C	80°C	90	6.5Kcy
Cu pure 4N (hard)	170°C	80°C	90	6.1Kcy
Cu-alloy 2N	170°C	80°C	90	12Kcy
Pd-coated Cu 4N	170°C	80°C	90	24Kcy no rejects

4N Cu pure
Worst case

2N Cu-alloy
Two times improvement

Pd-coated Cu
Best performance



ACCELERATION MODEL PROPOSAL

Accelerated Tests Results (Ncy_f=Weibull 30%)

WIRE Type Cu pure 4N (soft)	Twire ON	Twire OFF	∆Twire	Ncy to failure
TRIAL 1	170°C	110°C	60	24.7Kcy
TRAIL 2	140°C	50°C	90	26.6Kcy
TRIAL 3	170°C	80°C	90	6.5Kcy

The lifetime dependence on both Twire ON and ΔT suggests the Norris-Landzberg equation

Norris-Landzberg Equation

$$AF = \frac{N_1}{N_2} = \left(\frac{\Delta Tmax1}{\Delta Tmax2}\right)^n \times exp\left[\frac{Ea}{k} \times \left(\frac{1}{Tmax2} - \frac{1}{Tmax1}\right)\right]$$

- *Frequency factor ignored (tests at same frequency)*
- *Tmax=TwireON*

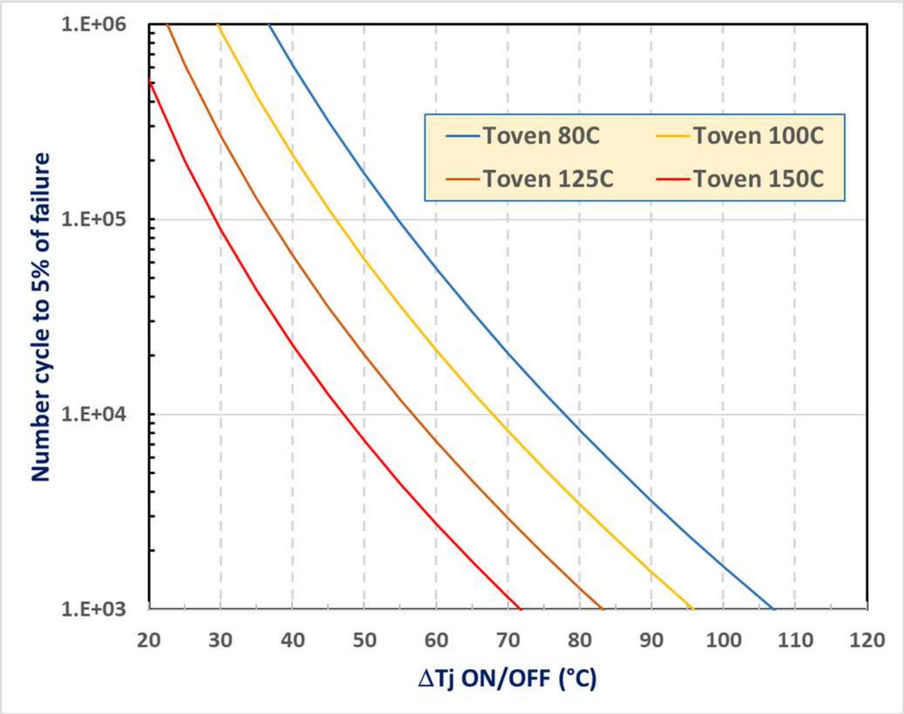
Parameters Estimated from Accelerated Tests

n=3.3	(Trial1 vs Trail3)
Ea=0.74eV	(Trial2 vs Trial3)

Allows Prediction for:
- **HTOL stress condition setting**
- **extrapolation to use condition**
- **customer application support**

Norris- Landzberg Prediction vs HTOL Setup

Number of Cycle to 5% Failure Curves
Cu 4N 1.2mil



EXAMPLE 1:

HTOL @ Toven=150°C, Tj ON=180°C (hottest point)
12000 ON/OFF cycles target (2khrs, OFF every 10min)
No issue expected

EXAMPLE 2:

HTOL @ Toven=100°C, Tj ON=190°C (hottest point)
6000 ON/OFF cycles target (1khrs, OFF every 10min)

Thermal fatigue wire crack failures expected

Possible Actions:

- Improve Rthj-amb to reduce ΔTj but same Tjavg
- Reduce Toven but same ΔTj prolonging test duration
- Splitted HTOL
  - Functional HTOL at high Tjavg with few ON/OFF
  - Customized HTOL for ON/OFF characterization
- Change the wire to Cu-alloy or Pd-coated wire for parts to be submitted to HTOL

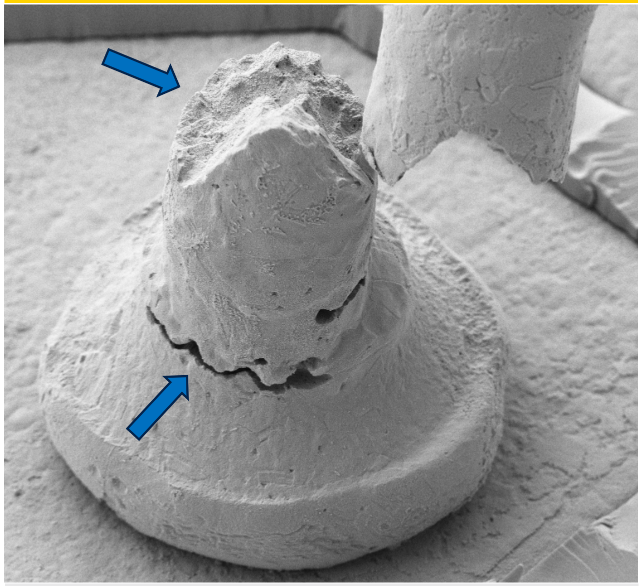
Failure Mechanism Characterization

Cu pure & Cu-alloy wires

SEM Inspection

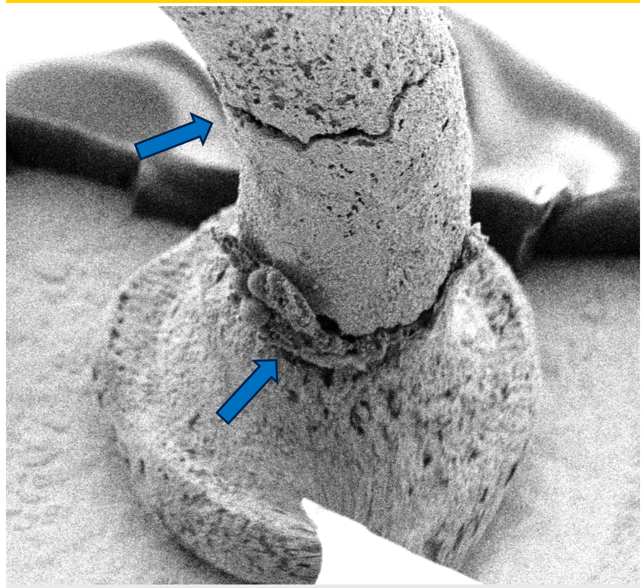
- Thermal fatigue crack confirmed on all inspected parts
- Major cracks are one at the ball-neck and the other ~30um above (wire kink)

Cu pure 4N (soft) wire



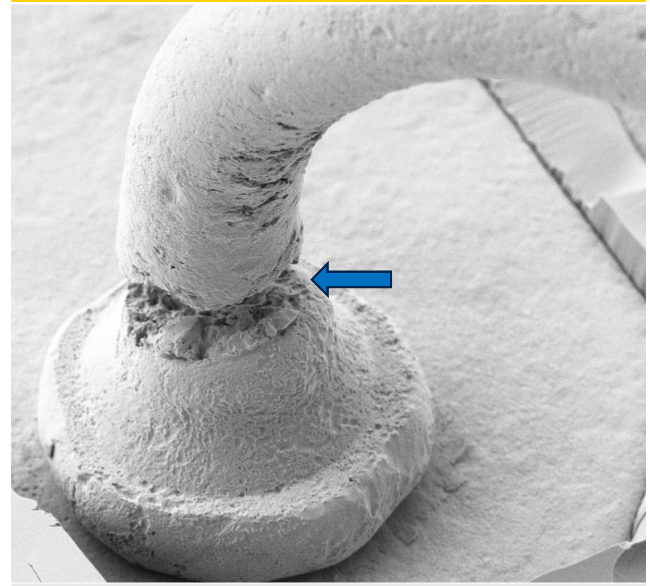
7 rejects inspected
Double major cracks detected

Cu pure 4N (hard) wire



5 rejects inspected
Double major cracks detected

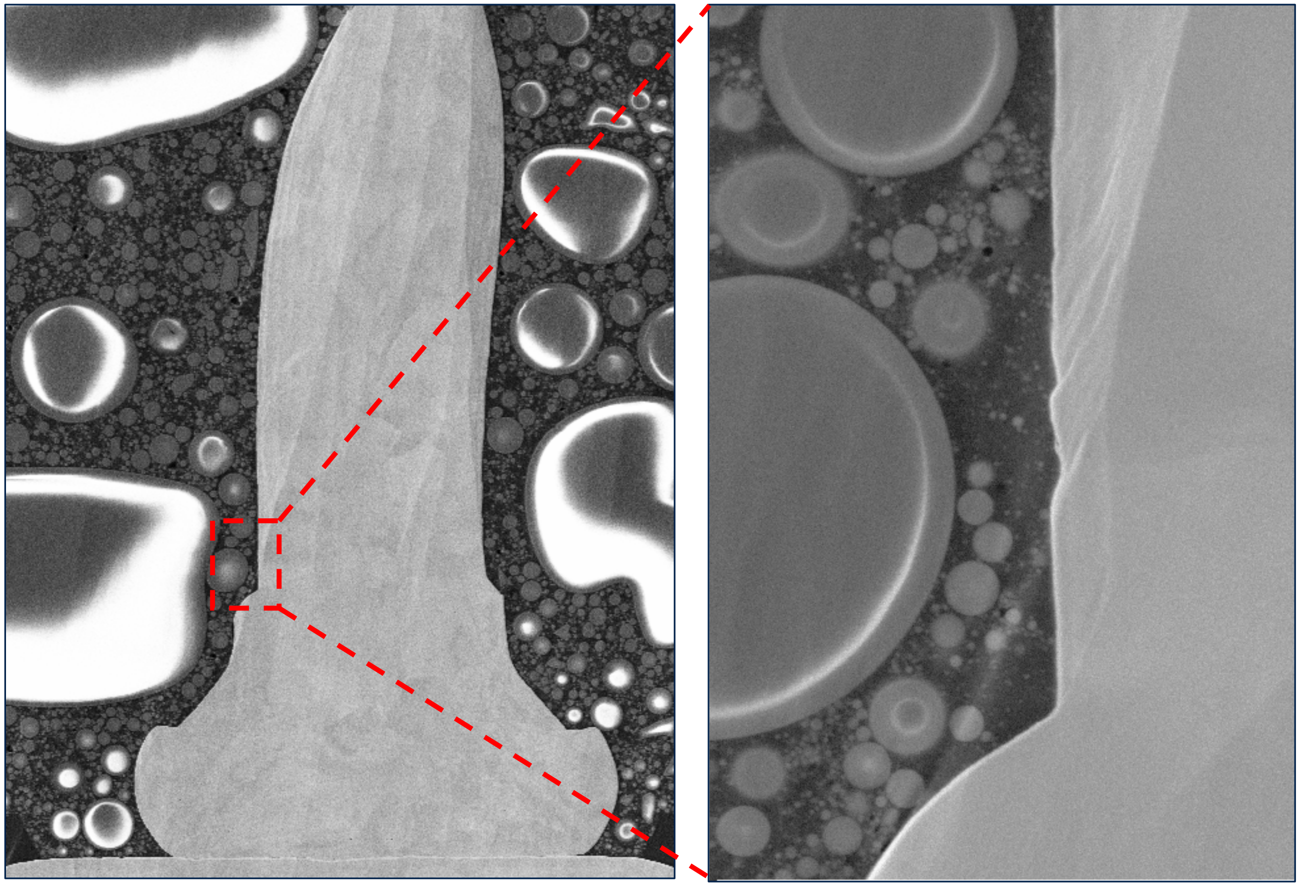
Cu-alloy 2N wire



2 rejects inspected
Single major crack detected

Failure Mechanism Characterization

Cu pure & Cu-alloy wires



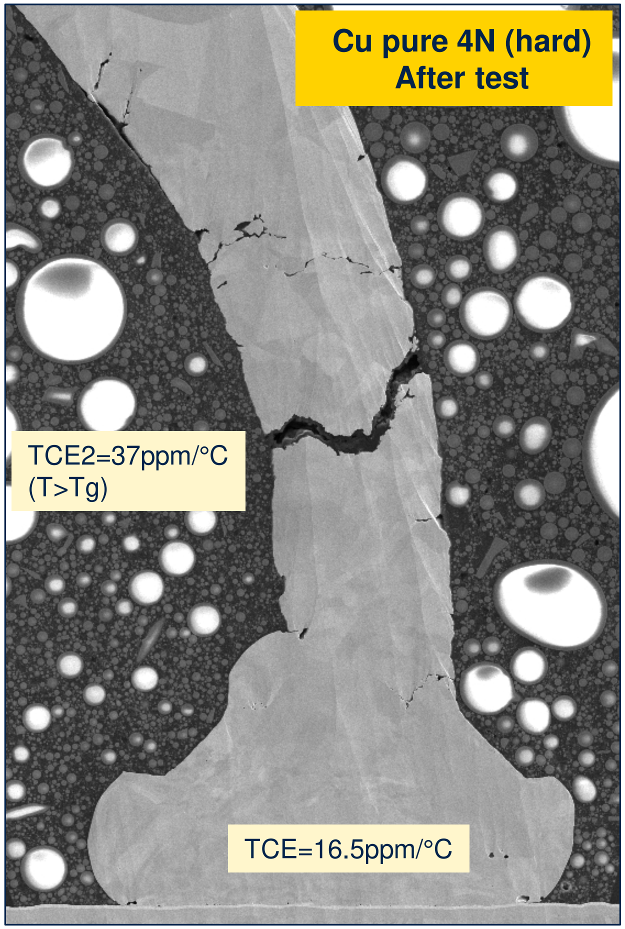
Virgin wire Cross Section

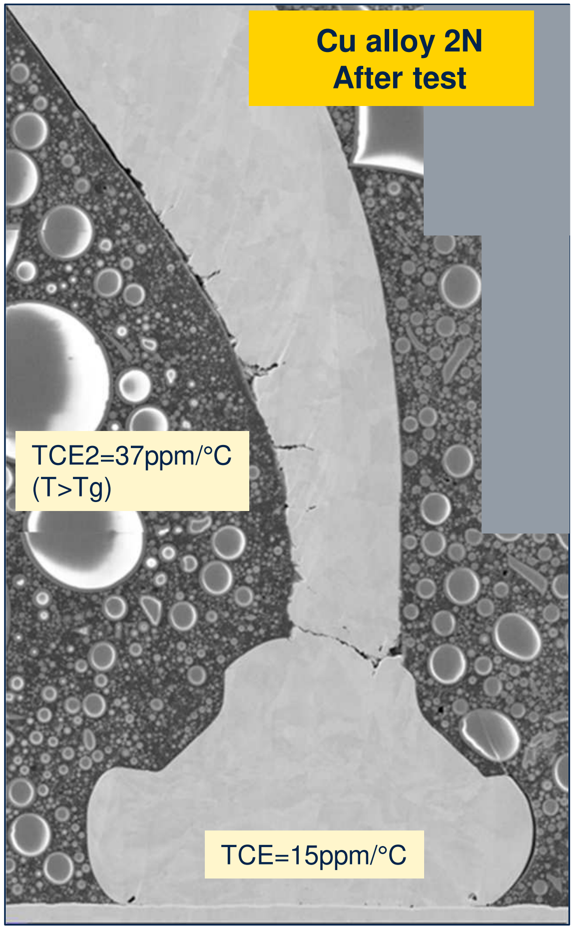
Virgin wire before thermal fatigue stress

Morphology:
- good adhesion between molding and wire
- almost smooth wire surface with small engravings

Similar morphology observed in both pure copper and copper-alloy wires

Failure Mechanism Characterization





Cu pure & Cu-alloy wires

Failed wire Cross Section

Huge thermal stress degradation detected

Morphology:

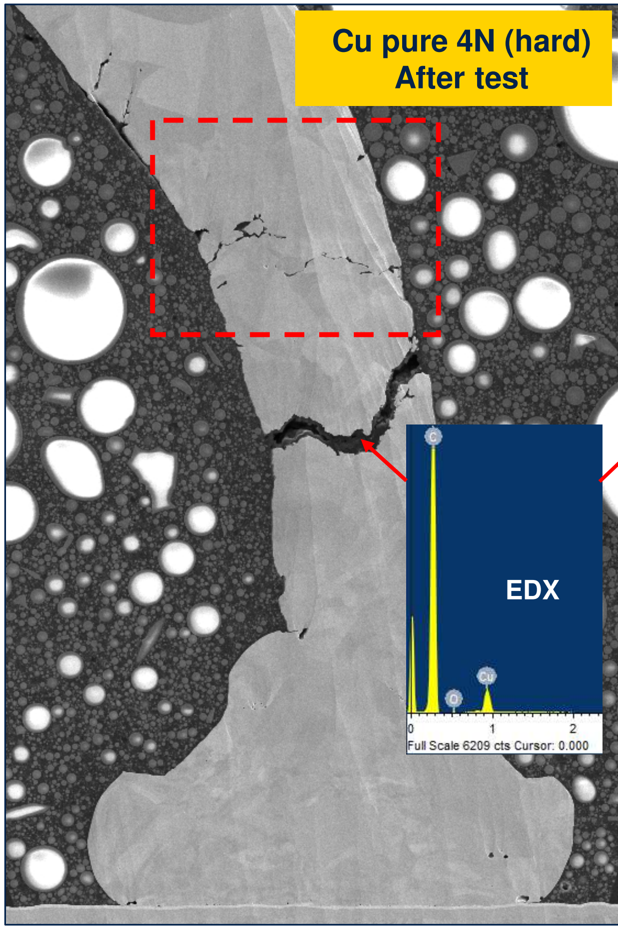
- Cu-alloy wire shows less damages than pure copper wire, in agreement with its longer lifetime
- both wires shows one major crack and several other perpendicular fractures along the wire, extending from the ball neck up to ~80 µm above
- crack initiation is at the wire surface
- In some points, the molding fills the crack, and no gap is created at the interface, suggesting a molding degradation also

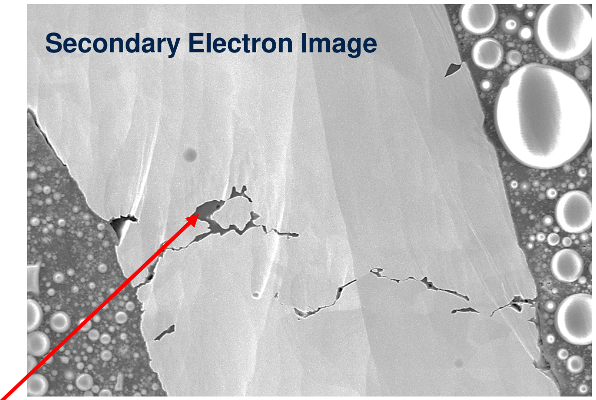
A robust wire surface interface is critical to mitigate thermal fatigue crack initiation and wire degradation

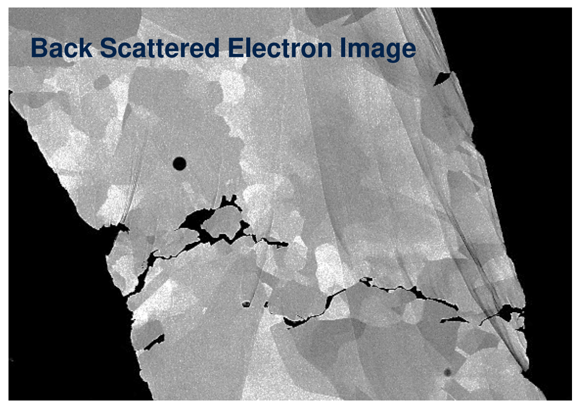
Failure Mechanism Characterization

Cu pure & Cu-alloy wires

Failed wire Cross Section







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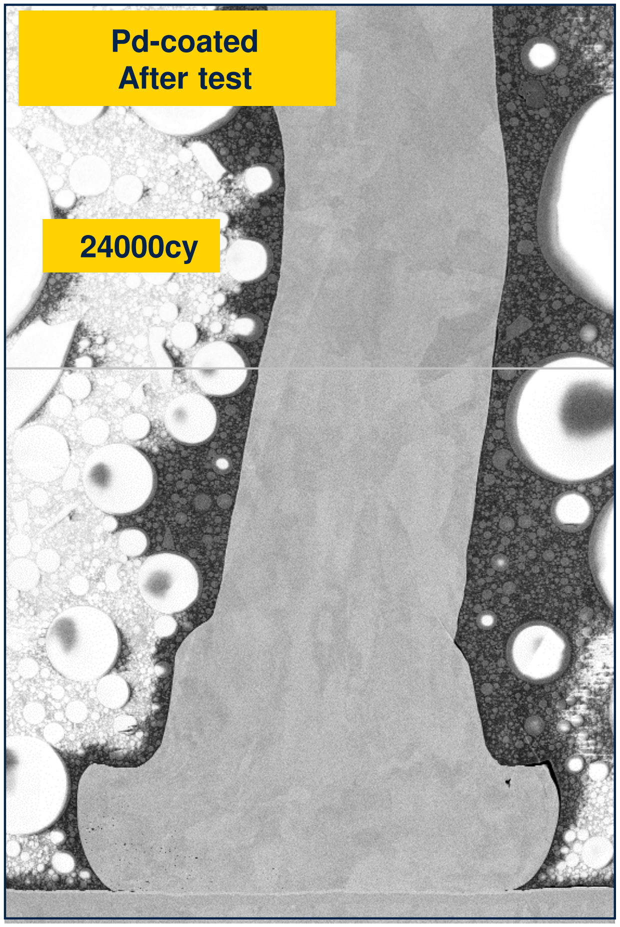
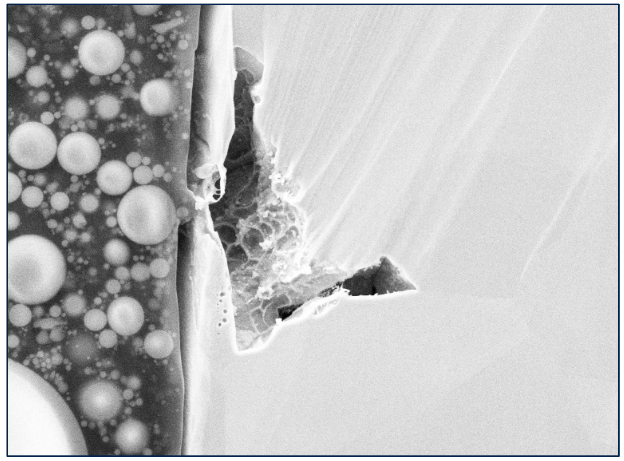
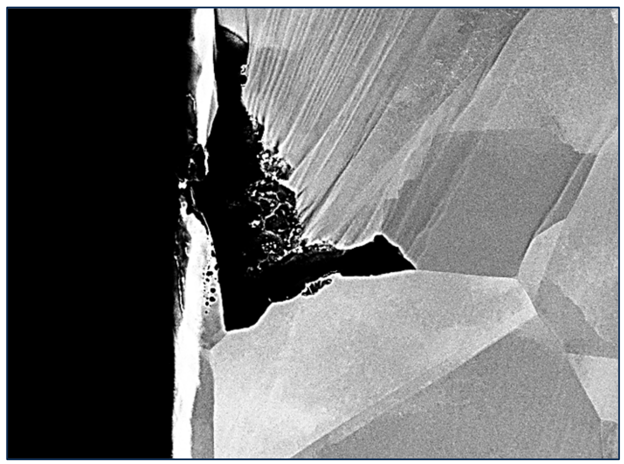
Failure Mechanism Characterization

Pd-coated 4N Cu wire

Cross Section







Minor damages detected

Morphology:

- few minor crack detected
- crack initiation is at wire surface in correspondence of Pd-coating deterioration point

The Pd coating is effective to delay crack initiation at wire surface

CONCLUSION

Thermal Fatigue in 1.2mil Cu Wire Bonds under Power Cycling Pilot Experiment Major Outcomes

ACCELERATION MODEL

The Norris-Landzberg equation is proposed as acceleration model
- parameter estimation n=3.3 and Ea=0.74eV

FAILURE MECHANISM

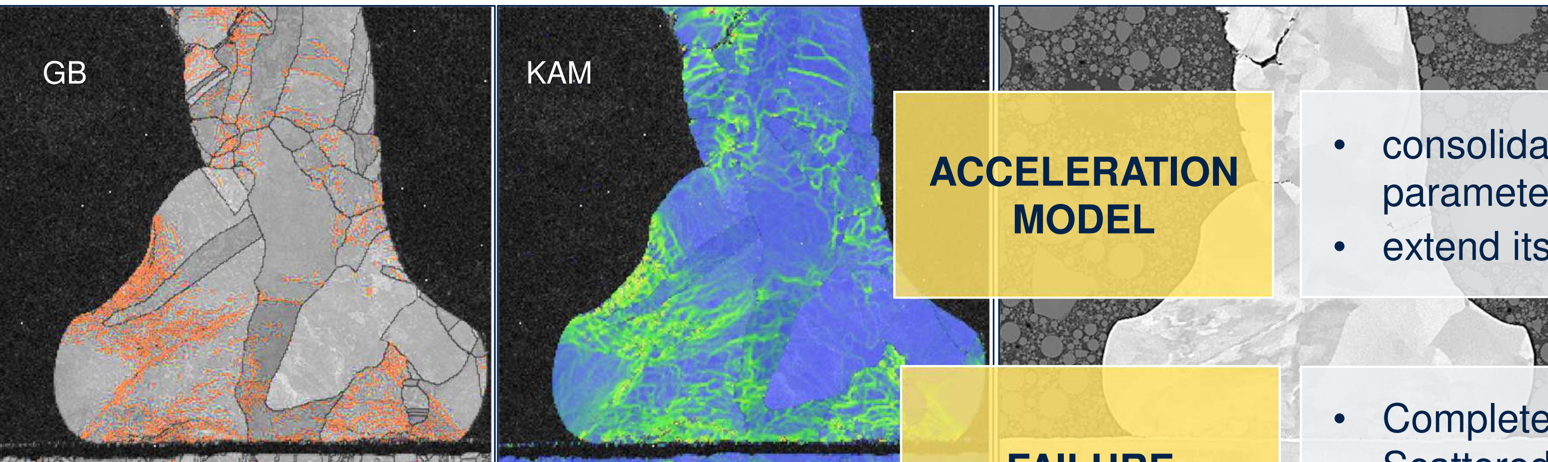
- In the cases of pure copper and copper alloy wires, thermal fatigue crack initiation occurs at the wire surface, where degradation of the molding compound is also observed
- A robust wire surface interface is critical to mitigate thermal fatigue crack initiation and wire degradation
- The Pd coating is an effective solution to protect the wire surface and delays crack formation

WIRE TYPE COMPARISON

- Cu pure 4N wire type showed the lowest lifetime
- The Cu-alloy 2N wire type doubles the lifetime of the 4N wire.
- The Pd-coated 4N wire is the best performer

NEXT STEPS

Further Investigation of the Acceleration Model and Failure Mechanism

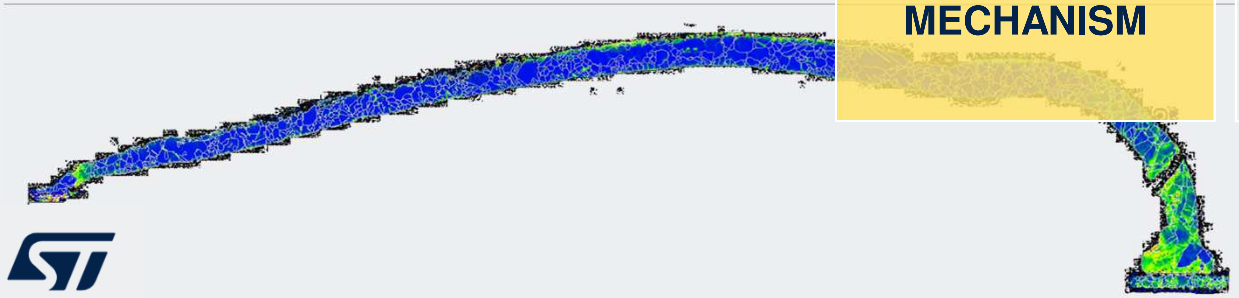


ACCELERATION MODEL

- consolidate acceleration model and parameter estimation for 1.2mil wire
- extend its application to 2mil wire

FAILURE MECHANISM

- Complete the Electron Back Scattered Diffraction analysis, now just started
- Finite Element Modeling



Thank You